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CURRENT PROBLEMS IN RESEARCH

Sediment Cores from the Arctic and Subarctic Seas

Distribution of fossils reveals shift of isotherm, change in ice movements, and continuity of ice cover.

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Sediment cores from the Arctic Ocean and the subarctic seas are of particular interest to students of Pleistocene climates. Hydrographic and ecological conditions in these waters must have varied drastically as the continental ice sheets advanced and wasted away repeatedly on the nearby land masses during the Pleistocene Epoch. If interdependence between changes in oceanic circulation and climatic changes on land obtained anywhere in the Northern Hemisphere, the interdependence should have been most distinctly expressed in this region. Evidence on this relationship, particularly on the cause-and-effect sequence, is, of course, of great importance in the search for a satisfactory hypothesis to explain glacial climates.

The collection of sediment cores at the Lamont Geological Observatory includes 58 cores from the Arctic Ocean and 26 cores from the Greenland and Norwegian seas. To the best of our knowledge this is the largest collection of sediment cores from the Arctic Ocean and subarctic seas to have been studied to date.

Navigation within the pack ice of the Arctic Ocean is impossible. Early exploration had therefore to be carried out by ships which drifted passively with the ice. The first crossing of the Arctic Ocean by drifting was accomplished by Nansen in his especially constructed ship, the *Fram*, in 1893. Nowadays, thanks to the aeroplane, ships can be dispensed with; men and equipment are simply put down on suitable masses of ice. Some camps on the ice have been occupied for years. They have been set up on ice floes (that is, slabs of frozen sea water) and on ice islands (masses of ice detached from the ice shelf of Ellesmere Island). The floe ice, because of its thinness (about 3 meters), gradually breaks up; the ice islands are much thicker, and some of them are believed to have been drifting for decades.

The Russian North Pole Drift Expedition in 1937–38 marked the beginning of an era of scientific exploration by scientists living on drifting ice. Russian Drift Expeditions since 1937 have made geophysical, meteorological, and bathymetrical observations on the North American as well as the Eurasian side of the Arctic Basin and over the North Pole.

The first American scientific observations from ice floes were made in 1951. At each station the observers spent only 6 hours on the ice. In March 1952 a station on Ice Island T-3, then located in the center of the Arctic Ocean, was established, and it was maintained until May 1954. Since then, scientific stations have been installed on several other ice islands and floes.

The sediment cores from the Arctic Ocean were raised during these drifting expeditions, between the early 1950's and 1962. Some of the cores were taken with a pistonless gravity corer and some with a miniature piston corer. The corers had plastic liners in which the cores were shipped to the Lamont Observatory. The cores from the Norwegian and Greenland seas were taken, from research vessels, with a corer designed by Ewing on the principle of the piston corer of Kullenberg (*1*). Figure 1 shows the positions of the coring stations, and Table 1 gives latitudes and longitudes of the stations, depths of water, and lengths of cores.

Sediments and Sedimentary Processes

Four kinds of sediments occur in the cores. These are: (i) sediment which has accumulated through the slow but continuous settling of mineral particles derived from the continents and hard parts of microscopic floating organisms; (ii) rock detritus transported from land by drifting ice; (iii) sediment transported from shallower water by turbidity currents; and (iv) mineral particles and particles of volcanic glass scattered by explosive volcanic eruptions.

Sediment of the first kind consists partly of mineral particles carried to the oceans by rivers and by winds, which ocean currents waft far out into the oceans. Because of the nature of the transporting process, only very finely divided material is transported, most of it of clay-size grade—that is, with particles smaller than 0.002 millimeter in diameter. For this fine sediment we use the term *lutite*, which indicates particle size only, in order to avoid the term *clay*, which has a mineral connotation. An important fraction of deep-sea lutites consists of finely divided quartz and minerals other

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than the clay group. An additional element in this kind of sediment consists of the hard parts of planktonic and benthic organisms. In some places the calcareous shells of planktonic or drifting foraminifera account for the major part of these sediments of slow and continuous accumulation.

Sediment of this kind is dominant in the upper parts of the cores which have accumulated since the disappearance of the Scandinavian ice sheet. However, as one would expect, particularly in the cores from the Arctic Ocean, a little ice-rafted material is sometimes present.

The second kind of sediment is known as "Glacial Marine sediment," a term first applied by Philippi (*2*) to sediments adjacent to the ice front in Antarctica which consist dominantly of clastic material, including coarse sand and fragments (of all sizes) of rocks transported by drifting ice—in particular, masses detached from glaciers and from inland ice rather than shelf ice.

Glacial marine sediments cored in the North Atlantic vary in color from brown to light gray. A glacial marine sediment occurs in the cores from the Norwegian and Greenland seas which is peculiar in being very dark gray or nearly black when wet. This same sediment has been observed by other marine geologists, in particular by Holtedahl (*3*), who has described six cores taken between Norway and Iceland. We discuss this nearly-black sediment later.

Evidence that graded layers (layers in which the particle sizes decrease with decrease in depth below the ocean floor) are deposited by turbidity currents has been presented by Kuenen (*4*) and by Ericson *et al.* (*5, 6*). Such layers vary in thickness from a few millimeters to several meters. Cores 20, 21, 23, and 24 contain graded layers. Figure 2 shows a graded sand layer in core 24. Good sorting of particle sizes at every level is a characteristic of these deposits which is helpful in distinguishing them from all other deep-water sediments.

No doubt turbidity currents (torrents of turbid water flowing down slopes on the ocean floor under clear water because of greater density due to suspended mineral particles) may be generated in various ways, but it is fairly certain that one common mode of origin is through slumping of masses of sediment which have become unstable because of accumulation on slopes. Evidence on this point has been presented by Heezen and Ewing (*7*).

Failure of lithological and faunal zones of the six cores of the Norwegian Sea profile (cores 2–5, 8, and 9) to correlate from core to core is evidence of loss of parts of the sedimentary sections by slumping, probably triggered by seismic shocks. Masses of sediment thus set in motion doubtless gave rise to turbidity currents which flowed down into the deepest part of the Norwegian Basin where the suspended sediment settled to form graded layers.

Pyroclastic sediment in the cores is represented by volcanic glass shards of two kinds. These are (i) brown, greenish brown, and black shards with spherical vesicles, and (ii) more or less curved or wavy films of nearly colorless glass, occasionally vesicular,

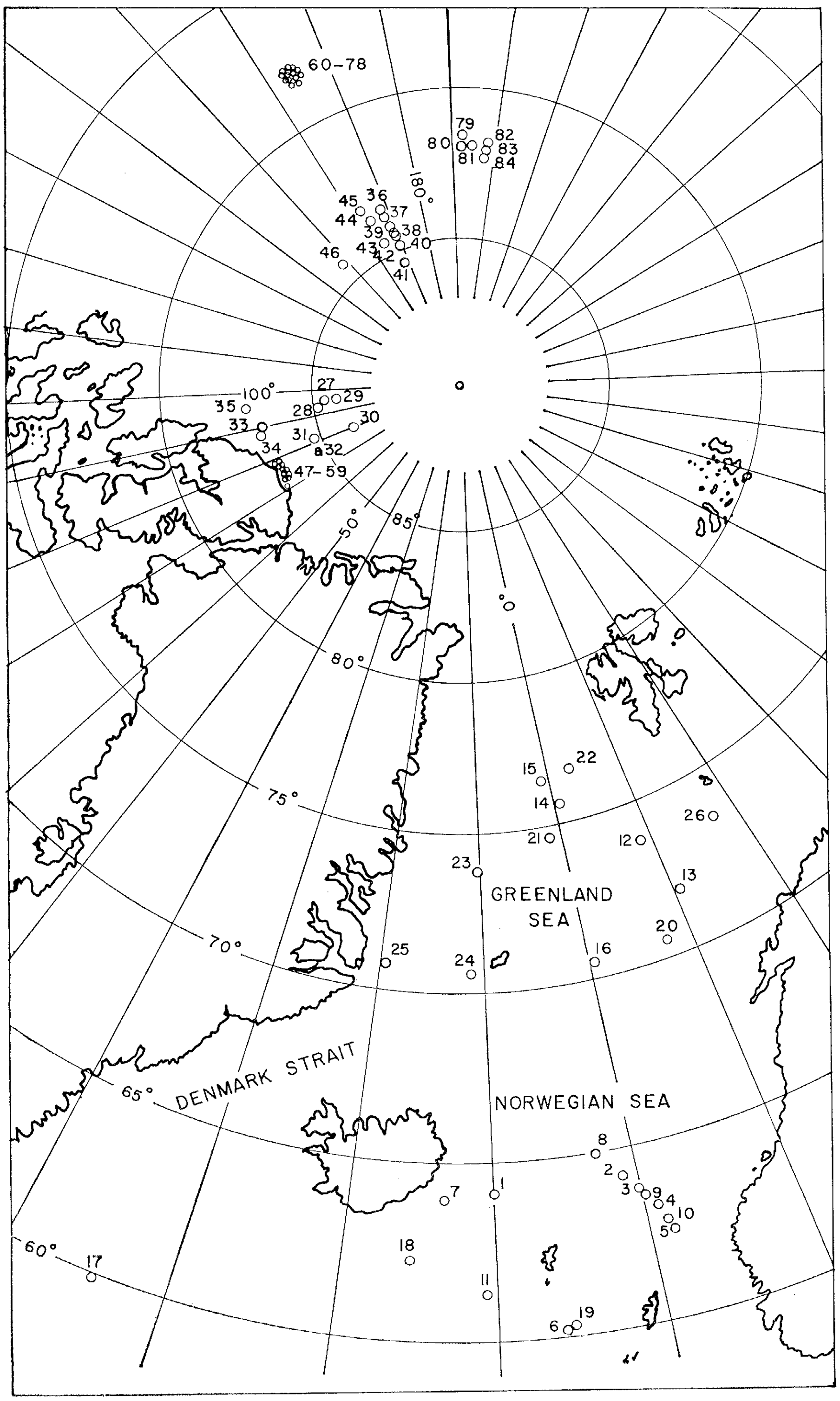

Fig. 1. Positions of the coring stations.

with the vesicles drawn into fine tubes.

The deeply colored shards are abundant in certain layers in cores from the vicinity of Iceland, particularly in cores 7 and 18. They are also conspicuous in core 24, from a point southwest of Jan Mayen. They occur only sporadically in other cores. The volcanoes of Iceland and Jan Mayen are obvious sources. The sporadic vertical distribution of these shards in the cores and their restricted areal distribution make them of little value as stratigraphical markers.

The colorless shards are very similar to those found by Bramlette and Bradley (*8*) in a suite of 11 cores taken along a traverse between Newfoundland and Ireland. Shards in both series have an index of refraction of 1.51, which is characteristic of a glass high in silica (about 70 percent), high in potassium, and low in calcium, iron, and magnesium.

Bramlette and Bradley considered the Azores, Iceland, and Jan Mayen as possible sources. They concluded that the northern islands were the more probable sources because alkalic volcanic rocks are associated with the basaltic volcanics of Iceland and Jan Mayen, and because evidence of relatively recent volcanic activity in Iceland had been found by Peacock (*9*). The distribution of the silicic shards in the cores we have studied supports their conclusions. The evidence favors Iceland as the source.

On 29 March 1947, 5 years before cores 7 and 12 were raised, Mt. Hekla in Iceland ejected vast quantities of ash and pumice. According to Henson (*10*) the initial column of steam and ash rose to a height of 20 kilometers. Although the finer ash particles must have been widely distributed over the sea south of Iceland by the north wind that was blowing at the time, no distinct layer of ash occurs at or near the tops of cores from this region. It is not certain whether this is due to disturbance of the uppermost layer of sediment in the cores in the process of taking and extruding the cores or whether it is due to mixing of the sediment by mud-feeding animals, as suggested by Bramlette and Bradley (*8*); this cannot be decided in the absence of short pilot cores taken and preserved in plastic tubes, and consequently with undisturbed tops.

The vertical distribution of the silicic shards points to the occurrence of an explosive eruption in postglacial time. These shards do not occur in a distinct layer which can be seen in the sliced cores. Instead they are scattered through a zone in which they can be detected only by examination of the material retained on a 74-micron sieve. By examining coarse fractions from closely spaced samples it is possible to determine a level of greatest abundance, which is presumably the level at which the shards were originally deposited. Since this level is some distance below the tops of the cores, one cannot conclude that disturbance of the sediment in handling the cores on board ship accounts for the scattering of the shards. The most probable explanation is that offered by Bramlette and Bradley (*8*): mixing by burrowing mud feeders.

The foraminifera in core 9 and in several other cores, from points farther south and therefore not discussed in this report, indicate that the explosive eruptions took place at some time after the postglacial hypsithermal interval. According to the chronology of Deevey and Flint (*11*), the eruption took place during the first millennium of the Christian era, and the relationship between the level of the silicic shards and the zone of Foraminifera which we believe marks the hypsithermal interval supports this conclusion. The wide distribution of the shards testifies to the enormous energy released by this volcanic outburst.

The cores from the Norwegian and Greenland seas (cores 1–26) give evidence of the same prevalence of slumping and deposition by turbidity currents which we have learned to expect in the Atlantic; we take this as a warning to proceed with caution in interpreting the climatic record in the sediments.

The seven cores (cores 2–5 and 8–10) of the Norwegian Sea profile show some of the many discontinuities in the sedimentary record. Figure 3 shows graphic logs of the cores. The sedimentary sections of six of these are certainly incomplete because of slumping. In the seventh, core 10, a gradational change from dark gray to brown glacial marine sediment indicates that the record is probably continuous, but even here continuity is not

Table 1. Locations, depths of water, and lengths of cores.

Core	Latitude	Longitude	Depth (m)	Length (cm)	Core	Latitude	Longitude	Depth (m)	Length (cm)
1	63°55′N	09°53′W	660	53	43	84°20′N	166°40′W	2416	149
2	64°18′N	01°21′W	2690	365	44	83°45′N	166°00′W	3008	151
3	63°47′N	00°25′W	2375	180	45	83°38′N	161°46′W	2510	175
4	63°07′N	00°50′E	1245	65	46	84°10′N	149°40′W	2035	116
5	62°33′N	01°49′W	640	300	47	83°19′N	75°30′W	183	19
6	60°08′N	05°57′W	1105	370	48	83°11′N	76°20′W	149	20
7	63°50′N	13°16′W	550	220	49	83°13′N	76°50′W	179	24
8	64°59′N	02°32′W	3180	55	50	83°18′N	77°10′W	70	5
9	63°28′N	00°04′W	2010	375	51	83°10′N	79°10′W	60	4
10	62°42′N	01°15′E	1005	365	52	83°15′N	78°15′W	184	21
11	61°17′N	10°39′W	1155	180	53	83°12′N	77°40′W	83	6
12	73°39′N	08°55′E	2105	58	54	83°14′N	75°55′W	162	20
13	71°53′N	11°40′E	2160	170	55	83°14′N	75°10′W	120	13
14	75°31′N	00°46′E	1755	110	56	83°17′N	74°50′W	107	13
15	76°24′N	01°02′W	3200	165	57	83°16′N	74°15′W	84	12
16	70°28′N	00°28′E	3035	120	58	83°12′N	73°55′W	87	8
17	60°02′N	34°12′W	2470	290	59	83°20′N	73°05′W	285	14
18	62°17′N	15°30′W	2195	14	60	77°41′N	164°03′W	267	15
19	60°20′N	05°40′W	860	120	61	77°41′N	164°03′W	271	25
20	70°29′N	07°57′E	2925	480	62	77°41′N	164°01′W	265	111
21	74°35′N	01°20′W	3750	445	63	77°42′N	163°59′W	260	134
22	76°31′N	03°34′E	2560	480	64	77°48′N	163°59′W	276	50
23	73°53′N	10°26′W	3110	460	65	77°47′N	163°52′W	265	259
24	70°33′N	11°14′W	715	460	66	77°42′N	164°10′W	262	137
25	70°48′N	19°45′W	1115	360	67	77°41′N	164°21′W	266	119
26	73°22′N	17°15′E	470	5	68	77°41′N	164°23′W	267	149
27	85°23′N	95°30′W	1450	14	69	77°40′N	164°37′W	301	15
28	85°20′N	93°30′W	1640	9	70	77°25′N	164°37′W	307	55
29	85°41′N	95°30′W	1900	16	71	77°24′N	164°37′W	295	246
30	86°11′N	80°00′W	2460	81	72	77°24′N	163°58′W	291	172
31	84°40′N	81°10′W	1500	15	73	77°24′N	163°51′W	285	101
32	84°40′N	81°00′W	1500	13	74	77°27′N	163°53′W	228	227
33	83°13′N	90°35′W	1720	75	75	77°30′N	163°56′W	282	251
34	83°11′N	89°20′W	1710	25	76	77°38′N	163°54′W	252	55
35	82°45′N	94°10′W	497	85	77	77°37′N	164°03′W	249	182
36	83°52′N	168°46′W	1591	27	78	77°41′N	164°11′W	261	157
37	83°52′N	168°12′W	1521	207	79	81°57′N	168°07′E	2800	44
38	84°12′N	168°33′W	2410	107	80	82°00′N	168°04′E	2875	80
39	84°21′N	168°49′W	2040	125	81	82°06′N	166°27′E	2775	50
40	84°28′N	169°04′W	1935	125	82	82°11′N	162°44′E	2775	87
41	85°15′N	167°54′W	1840	85	83	82°03′N	162°58′E	2780	87
42	84°22′N	170°07′W	1912	176	84	82°08′N	161°37′E	2800	98

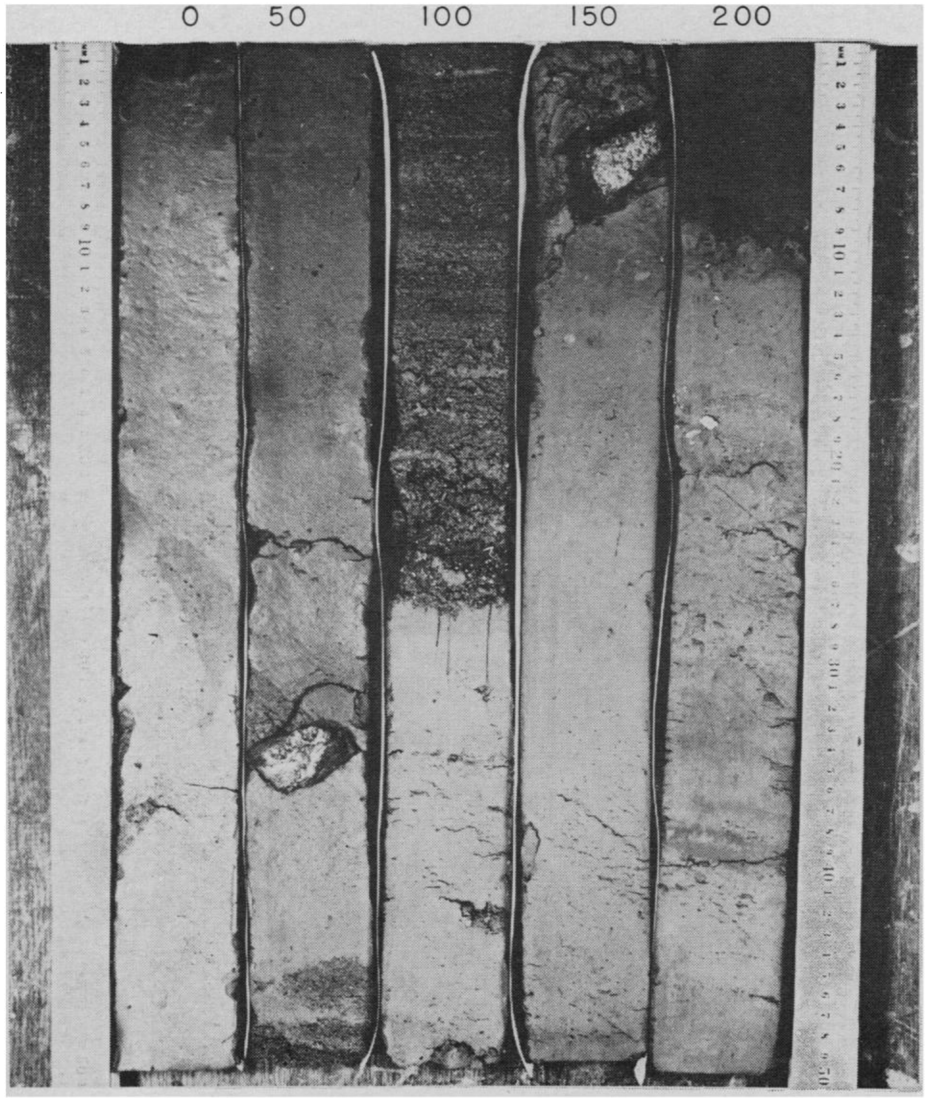

Fig. 2. Sections of core 24 showing graded sand layer, fragments of sandstone, and granitic pebble. The length of each section is 50 centimeters. The width of the core section is 6 centimeters.

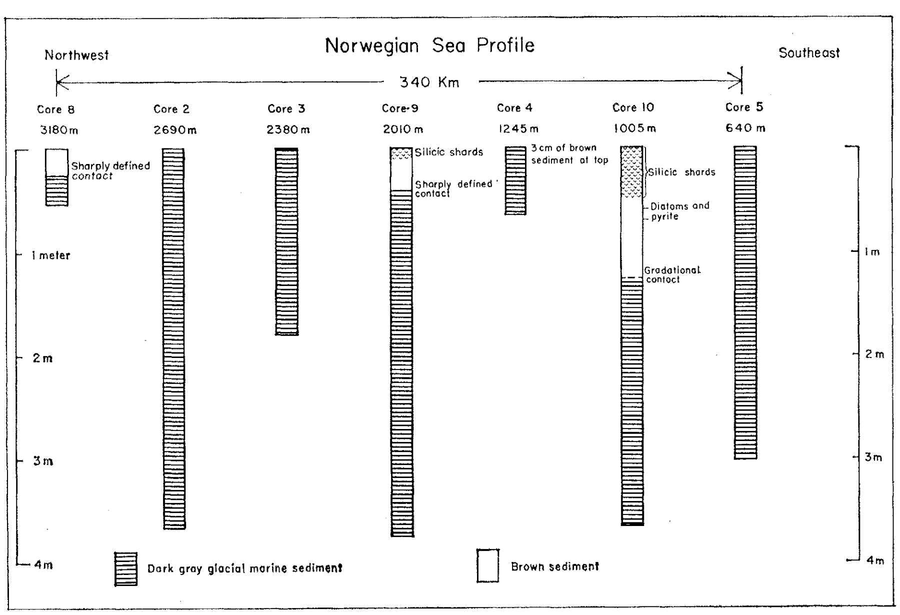

Fig. 3. Graphic logs of cores along the Norwegian Sea profile.

proved; the gradational change may be due to mixing of the two kinds of sediment by mud-feeding burrowers, and not to a gradual change in the conditions of sedimentation. As no other core in the suite contains the same sedimentary sequence, we cannot use cross correlation to prove the continuity of sediment accumulation in core 10.

Four cores from the Bering Strait sector of the Arctic Ocean (cores 38–41) provide a good example of evidence for continuity by cross correlation. Figure 4 shows the alternating layers of light and dark brown glacial marine sediments and their excellent correlation from core to core.

In one important respect all these sediments from the Arctic Ocean and subarctic seas differ from those of the mid-latitude Atlantic—that is, in prevalence of ice-rafted material or glacial marine sediment. According to Schwarzacher and Hunkins (*12*), who analyzed dredge samples from the Arctic Ocean, sedimentary rocks predominate in the ice-rafted detritus, with carbonate rocks accounting for 40 to more than 50 percent, by weight, of the material coarser than 3 millimeters in diameter. Similar detritus occurs at various levels in the Arctic Ocean cores.

A glacial marine sediment occurring only in the cores from the Norwegian and Greenland seas is peculiar in containing quantities of dark gray to black carbonaceous shale. As one would expect, the particles of this soft sediment rarely exceed a few millimeters in diameter, and much of it occurs in the form of rock flour. It occurs particularly in the cores of the Norwegian Sea profile (cores 2–5 and 8–10) and in cores 16 and 26 from the Greenland Sea.

The glacial marine facies and the presence of a few Pleistocene foraminifera prove that this sediment was deposited on the floor of the Norwegian Greenland Basin during the Pleistocene. The washed coarse fractions from samples of the sediment contain Upper Cretaceous fossils and cubes of pyrite. Particularly well represented are minute calcareous prisms from the shells of *Inoceramus*, a genus of clams which became extinct at the end of the Mesozoic Era. These fractions also contain a few fragments of bryozoans and Upper Cretaceous foraminifera such as *Globigerina cretacea* and species of *Globotruncana*, *Gümbelina*, and *Sten-*

siöina. We surmise that the bryozoans, the Upper Cretaceous foraminifera, and particles of white chalk, which also occur sparingly in these cores, were dropped by drifting ice, which originated on the Cretaceous sediments of Denmark. However, at least some of the *Inoceramus* prisms are associated with the carbonaceous shale, as shown by the occurrence of prisms embedded in particles of shale and by the particular abundance of the prisms and even of small fragments of the shells of *Inoceramus* in core 26, from a station south of Björnöya, where no chalk particles or Cretaceous foraminifera are found.

Had the source of the *Inoceramus*-bearing carbonaceous shale been in Central Europe or the British Isles, much dilution by noncarbonaceous detritus from the Scandanavian Peninsula would be expected, particularly in a region only 130 kilometers from Björnöya, such as that in which core 26 was taken. To the best of our knowledge no similar shale occurs on the Scandinavian Peninsula. On the other hand, Klenova (*13*) states that dark gray to black shales, some containing concretions of pyrite, plant detritus, and coal seams, occur on various islands of the Svalbard and Franz Josef archipelagos. From this we conclude that the most probable source of the black shale was among the islands north of Norway. This implies that the net direction of movement of drifting ice during the last ice age in the eastern half of the Norwegian and Greenland seas was from north to south. The fact that the white chalk particles and the Cretaceous Foraminifera sparingly present in the cores of the Norwegian Sea profile are absent from cores 16 and 26 suggests that the chalk came from the south, possible sources being Denmark and England. This supposition implies that there was a confluence of ice drifting from the north and ice drifting from the south in the vicinity of the Norwegian Sea profile. Since, however, the carbonaceous shale particles greatly outnumber the chalk in these cores, it is probable that the dominant direction of ice movement was from north to south even in this southern part of the Norwegian Sea.

Postglacial sediment overlying the dark gray glacial marine deposit is absent in cores 2, 3, and 5 of the Norwegian Sea profile. Removal by recent slumping is the most probable explanation of the absence of this sediment. Postglacial steepening of the slope of the sea floor here, in consequence of isostatic rise of the Scandinavian Peninsula after removal of the enormous load of ice that formerly covered Scandinavia, is a possible explanation of the instability of sediment along this profile. In cores 4 and 8 the sharply defined lithological break at the top of the dark gray glacial marine sediment almost certainly represents a discontinuity due to removal of some part of the section by slumping. In core 9 the postglacial section is complete in the sense that it includes a layer containing abundant shards of silicic volcanic glass, a layer which occurs in the postglacial section of undisturbed cores from other areas. However, the abrupt change at the lithological boundary suggests discontinuity.

Only core 10, in which there is gradation from dark gray glacial marine into brown glacial marine and finally into postglacial sediment, with the usual succession of zones defined by planktonic foraminifera and shards of silicic volcanic glass, provides sugges-

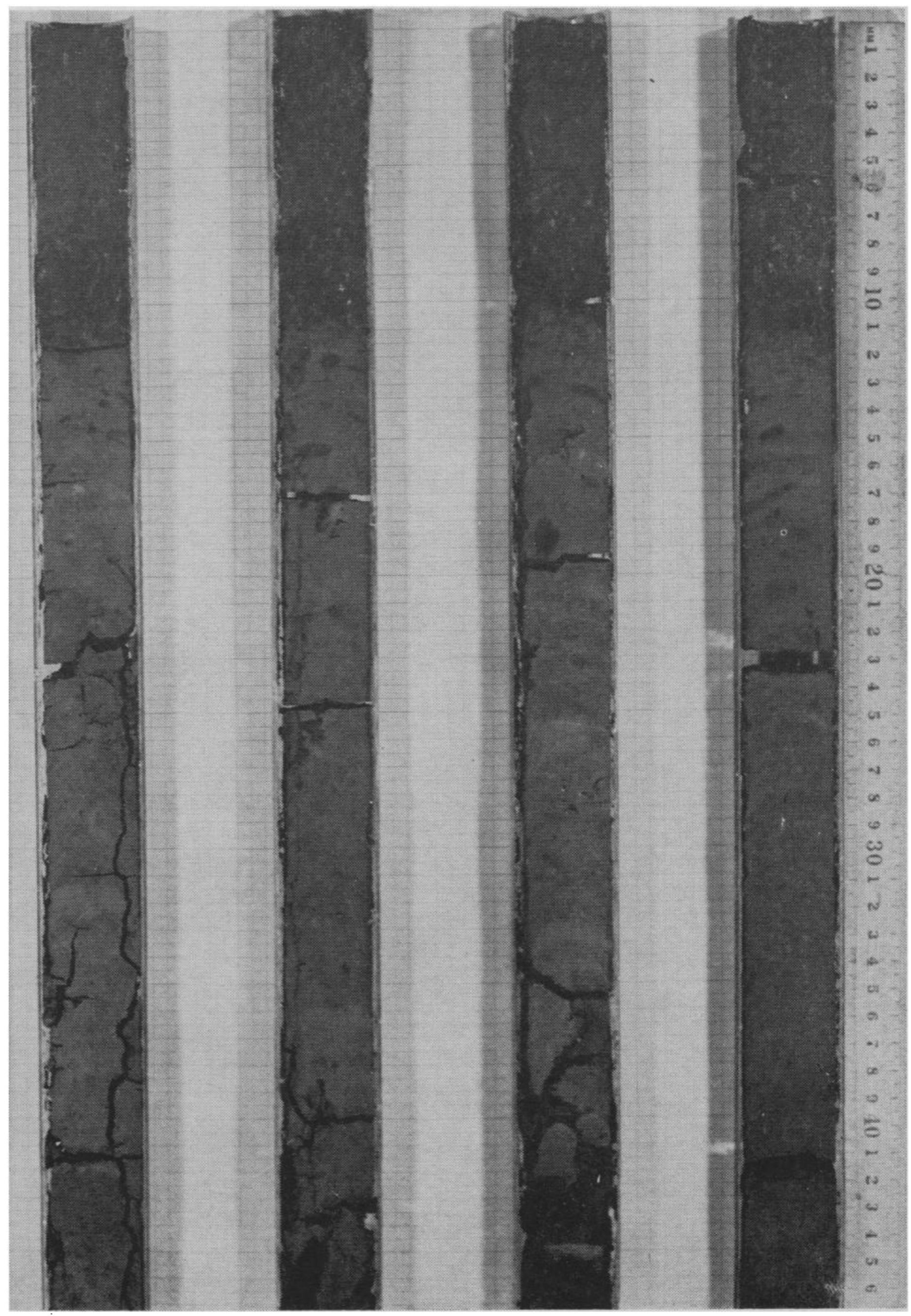

Fig. 4. Top sections of cores 38, 39, 40, and 41, showing lithological correlation. The length of each section is 47 centimeters. The width of the core section is 3 centimeters.

tive evidence of continuity, but this "evidence" is not proof. Thus it is possible that the dark gray glacial marine sediment accumulated during some earlier ice age than the last.

In summary, the dark gray sediment owes its color to more or less finely divided carbonaceous shale of Mesozoic age. The material was transported by bergs probably calved from the ice cap that formerly covered the Svalbard-Björnöya region. The sedimentary sequence in the cores indicates that toward the close of the last glaciation a change in the dominant process of deposition took place; accumulation of ice-rafted detritus from the north gave way to accumulation of finely divided and thoroughly oxidized mineral matter part of which was formed by subaerial erosion of the adjacent lands and part of which was transported by current from the North Atlantic.

Arctic Ocean Cores

The excellent correlation of alternating dark and light brown layers of foraminiferal lutite in cores 38 to 41 from the Arctic Ocean has been mentioned as evidence of continuous accumulation uninterrupted by slumping or by intercalation of layers deposited by turbidity currents. Study of the faunal zones in washed samples from these cores shows correlation of the fragments that parallels the correlation by lithology and color which is clearly apparent in Fig. 4.

Arctic Ocean cores 27 to 37, 42 to 46, and 60 to 84 consist mainly of fairly uniform, silty, grayish brown lutite. One of thse cores (core 46) is remarkable, however, in containing a few centimeters of highly altered igneous rock in its lower end. The core, 116 centimeters long, was raised from a depth of 2030 meters in an area where the echo sounder showed a steep slope on the Alpha Ridge, a ridge more or less parallel to the great Lomonosov Ridge, which extends across the Arctic Basin from Greenland to the New Siberian Islands. The Alpha Ridge was named after the ice island from which this core was taken.

The bottom of this core enters 5 centimeters of soft material composed of fairly closely packed spheres, 0.05 to 0.10 millimeters in diameter, of a clear, colorless mineral in a rusty clayey matrix. We take this mineral to be a thoroughly altered vesicular volcanic glass, the vesicles being lined by a secondary mineral, probably a zeolite. We believe that this is reliable evidence of former extrusive volcanism on the Alpha Ridge. Although the overlying sediment contains several ice-rafted rock fragments, it is most improbable that the altered rock was ice-rafted; it is far too friable to survive ice-rafting. Ninety percent of a sample subjected to our method of washing passed through the 74-micron sieve. Alteration must have taken place *in situ*. However, shards of volcanic glass in other Arctic Ocean cores at greater depths below the sediment surface show little, if any, alteration. It is highly improbable that this particular mass of glass could have reached so complete a state of alteration in the time represented by the thickness of overlying sediment. If the alteration took place *in situ*, the degree of alteration poses no problem. The absence of a thick cover of sediment can be explained as the result of removal of sediment by slumping; the soft altered material could itself have taken part in a slump. A thin film of manganese oxide coats the surface of the altered rock. Had the surface been exposed for long, through the scouring action of ocean current, for example, a much thicker layer of manganese oxide would be expected. Several burrows of marine animals penetrate the altered rock to a depth of about 2 centimeters—clear evidence that the rock was thoroughly altered before exposure by slumping.

Cores 47 to 59 were raised from the shelf off Ellesmere Island. In this region of shallow water one would expect bottom configuration to have played an important part in determining the areal distribution of fine sediment. Evidence from other, comparable areas shows that current-scour causes silt and lutite grades to accumulate preferentially in depressions, with the result that the rate of sediment accumulation may be many times higher in depressions than on rises. From the percentage of coarse fraction (particles of diameter $> 74\ \mu$) in samples from the tops of these cores, it appears that little or no coarse ice-rafted sediment has accumulated in this shelf region. With one exception, samples from the tops of the cores contain no more coarse material than would normally occur at shallow stations adjacent to land. In contrast, samples from the bottoms of the longer cores from the shallower stations (cores 48, and 54–58) contain much higher percentages of unsorted coarse rock detritus, including particles of granule and pebble size. This unsorted coarse material does not occur in the bottom samples of cores from the deeper stations (cores 47, 49, 52, and 59). If the unsorted detritus was distributed by ice-rafting, as seems most probable, it should also occur at the deeper stations. This apparent discrepancy probably is due to the much higher rate of accumulation of fine sediment at the deeper stations on the shelf off Ellesmere Island since ice-rafting ceased, with resulting deep sediments which prevented the coring tube from reaching the layer of abundant coarse detritus.

A marked increase, from bottom to top of the cores, in the proportion of organic remains is another bit of evidence for a fairly recent change in the environment. This might be explained as being due to a decrease in the rate of accession of terrigenous sediment, which would dilute the organic fraction. However, the fact that there is an increase in number of species as well as in number of individuals supports our inference that the vertical change does record an improvement in the ecological conditions. Whether this change represents the close of the last ice age or a more recent minor climatic fluctuation cannot be decided from the data now available, but the low rate of sediment accumulation to be expected at these shallow stations on the shelf off Ellesmere Island leads us to believe that the moderation in climate took place at the close of the last ice age.

One alternative to our interpretation deserves mention: that the change was due to a recent rise in sea level. It has been established beyond reasonable doubt that a rise in sea level of the order of 100 meters took place at the close of the last ice age in consequence of the return to the oceans of the water previously held on the continents as vast ice sheets. However, it is improbable that the increase in organic remains can be due to deeper water because a similar increase occurs in other cores from the Arctic Ocean from depths of thousands of meters, where rise in sea level could not have had an appreciable effect on ecological conditions. Furthermore, since Sverdrup (*14*) has reported the occurrence of marine terraces on Ellesmere Island up to 180 meters above sea level it is most probable that the eustatic rise in sea level has been more than compensated by postglacial uplift of the sea floor in this near-shore region.

The abundance of the tests of the planktonic species of Foraminifera, *Globigerina pachyderma*, in samples from the tops of the cores from the shelf off Ellesmere Island is remarkable. Although the species occurs in abundance at deep stations at high latitudes in the North Atlantic, it is never found in shallow-water shelf sediments. Apparently this species, adapted to near-freezing temperatures, lives close to the surface in the Arctic Ocean but seeks deeper, and therefore colder, water in the North Atlantic.

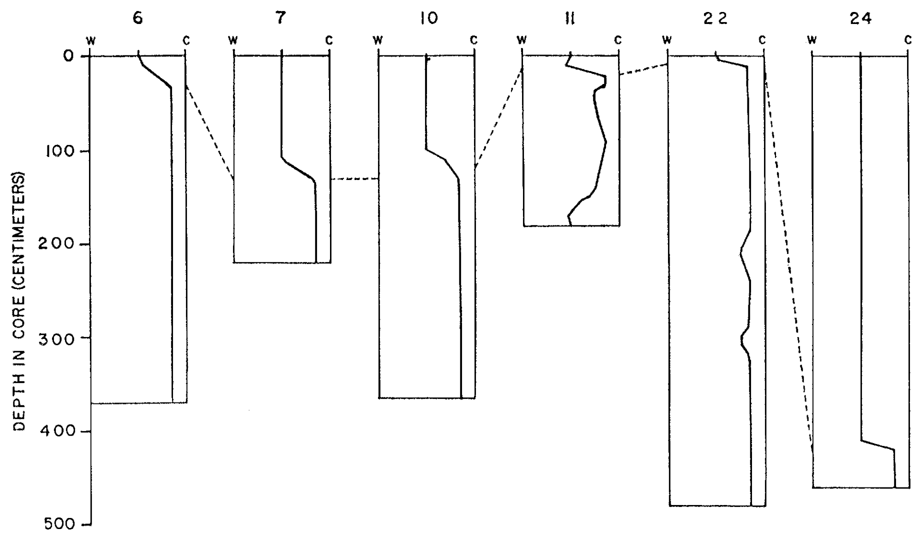

Fig. 5. Climatic curves based on the relative numbers of warm- and cold-water planktonic Foraminifera in six deep-sea sediment cores from subarctic seas. *W*, Relatively warm climate; *C*, relatively cold climate. Present climate is plotted on the midpoint between *W* and *C*, and inferred past climate is plotted with respect to it. The dashed lines connect faunal and climatic changes believed to have occurred at the end of the last ice age.

Distribution of Planktonic Organisms

The following planktonic Foraminifera occur in the subarctic cores: *Globigerina pachyderma, G. bulloides,* and *G. inflata.* Tests of *Orbulina universa, Globorotalia scitula, G. hirsuta,* and *G. truncatulinoides* (all species of planktonic Foraminifera) are sparingly present in sediment samples from stations directly southwest of the Greenland-Scotland Ridge, but we have found none in any core northeast of the ridge. Evidently the ridge was an effective barrier to the spread of these species during the Late Pleistocene.

In our opinion only one species of planktonic Foraminifera, *Globigerina pachyderma,* occurs in the cores from the Arctic Ocean. Admittedly there is variation among the tests, but complete intergradation between the forms leads us to conclude that all belong to a single species. Since we have not been able to distinguish any geographical pattern of distribution or vertical change in the relative abundances of the different forms in the cores, we doubt that it would serve any useful purpose to split the species into racial groups.

Globigerina bulloides has been reported as occurring in the sediments of the Arctic Ocean. We believe that the very small *G. bulloides*-like form which occurs with *G. pachyderma* is the latter in an immature stage of development.

No shells of planktonic snails or pteropods occur in the cores from the Norwegian and Greenland seas. However, a small coiled pteropod is found in the upper parts of some cores from the Arctic Ocean. It differs in some respects from *Limacina helicina* of the Atlantic and is closely similar to *Limacina pacifica,* as described by Dall (*15*), facts which suggest to us that it entered the Arctic Ocean by way of Bering Strait, a conclusion in harmony with evidence cited by Ekman (*16*). According to Ekman several zoogeographers have concluded, on what he regards as good grounds, that a considerable part of the fauna of the Arctic Ocean derives from the North Pacific. More recently Treshnikov (*17*) has cited the finding of Pacific species of planktonic organisms, *Calanus tonsus* and *C. cristatus,* in the Arctic Ocean as evidence that Pacific waters penetrate to the center of the Polar Basin.

In view of this conclusion it is probable that a dam across Bering Strait, such as the Russian P. M. Borisov has proposed might be constructed, would have a profoundly disturbing effect upon the zooplankton of the Arctic Ocean, and thus indirectly upon other forms of life there.

The Climatic Record

Faunal zones defined by variations in relative number of tests of species of planktonic Foraminifera have been observed and cross-correlated in many sediment cores from the Atlantic and connecting seas. These zones were first recognized by Schott (*18*), who surmised that they recorded climatic changes of the Pleistocene. Subsequent micropaleontological studies of deep-sea sediment cores by Cushman and Henbest (*19*), Schott (*20*), Phleger, Parker, and Peirson (*21*), Kane (*22*), and Ericson *et al.* (*6, 23*) have supported Schott's original surmise. The methods of faunal analysis used by these investigators all depended upon variations in relative numbers of certain species of planktonic Foraminifera which are known to be sensitive to temperature.

In our interpretation of the assemblages we have construed increases in the frequencies of *Globigerina pachyderma, G. bulloides,* and *G. inflata* with respect to other species as indicating decrease in temperature, and vice versa. This interpretation is based on the present-day distribution of the various species. For instance, we know from the top samples of the cores that no species of *Globorotalia* occurs to the north of the Greenland-Scotland Ridge, whereas these species are increasingly abundant southward from the ridge. Similarly we regard increase in the frequency of *Globigerina pachyderma* with respect to frequencies of *G. bulloides* and *G. inflata* as an indication of decreasing temperature. This inference is supported by the observation that *G. pachyderma* is the only species of planktonic Foraminifera which can tolerate the rigorous conditions of the Arctic Ocean.

A continuous climatic record, as inferred from relative frequencies of planktonic Foraminifera, was found in only six of the cores from subarctic seas. The results of our interpretation are shown in Fig. 5. The dashed lines connect points indicating a faunal change which is considered to mark the end of the last ice age. Radiocarbon dating of samples from sediment cores raised in the Atlantic and Caribbean has shown that a similar faunal change, indicating a moderation in climate, took place about 11,000 years ago (see *6, 24*). Particularly significant is the evidence at 160 and 170 centimeters in core 11. We believe that this zone corresponds to the X zone, or Würm interstadial, described by Ericson *et al.* (*6*) in various cores from more southerly stations. According to the chronology proposed by these investigators (*6*), the time interval represented by the sediment section down to 150 centimeters is about 65,000 years. This estimate gives a mean rate of sediment accumulation of 1 centimeter in 430 years.

Bandy (*25*) and Ericson (*26*) have found an interrelationship between surface-water temperature and the dominant direction of coiling of *Globigerina pachyderma*. Figure 6 shows the areal distribution of coiling dominance in top samples from most of the cores. Right coiling is dominant in the tops of only two cores (cores 11 and 18). In core 11, left coiling is dominant below 20 centimeters. In core 18, which is only 14 centimeters long, no change in coiling dominance occurs. From the change in coiling from left to right in core 11, and in other cores cited by Ericson (*26*) from more southerly stations, we infer that a northward shift of the 7.2°C isotherm for April (see Fig. 6) took place probably at the close of the last ice age. The fact that strong dominance of left coiling prevails at all levels in all cores from stations north of the Greenland-Scotland Ridge confirms our surmise, based on relative frequencies of planktonic species of Foraminifera, that the 7.2°C isotherm for April has never extended into the Norwegian Sea during the time represented by the cores.

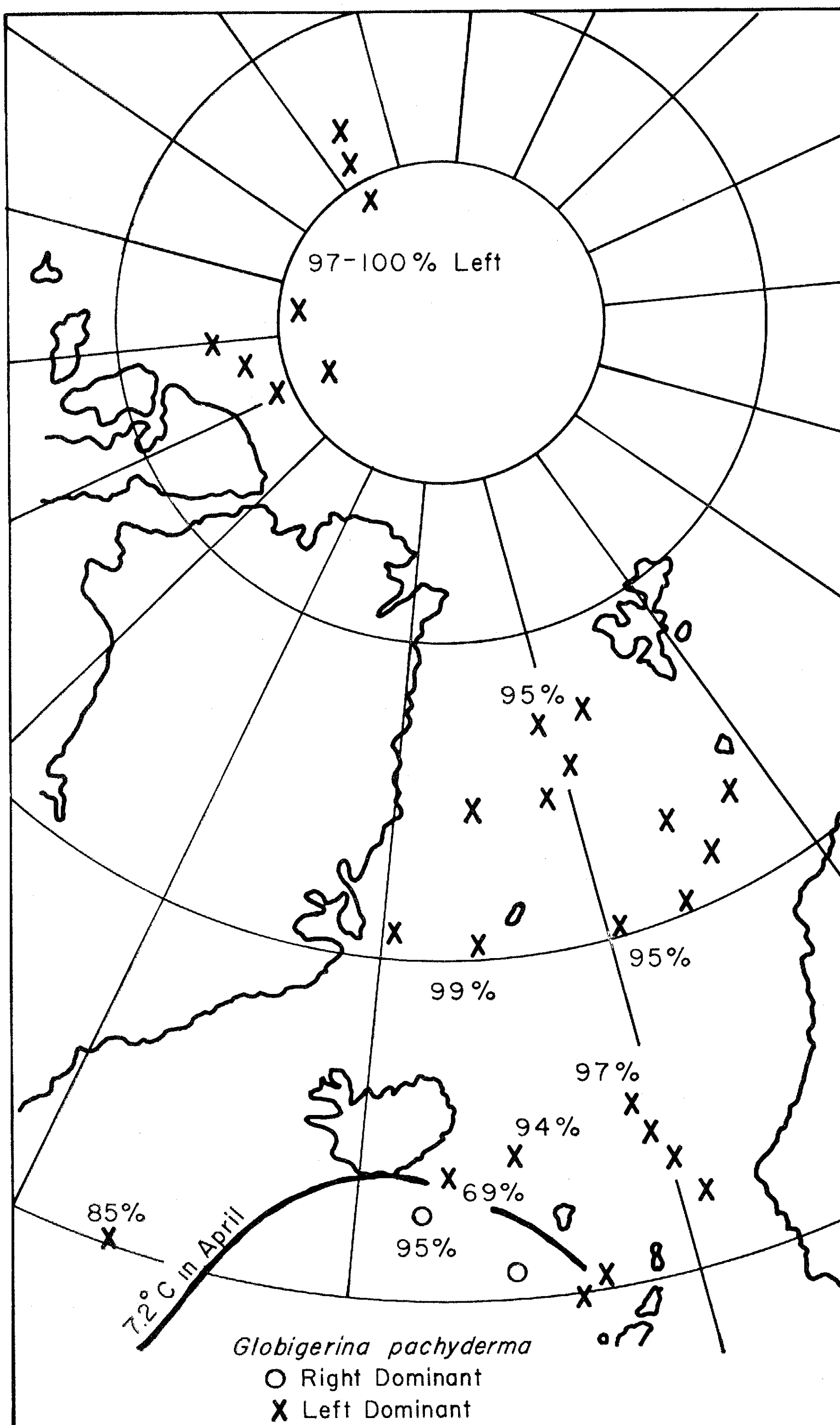

Fig. 6. Distribution of right-coiling and left-coiling shells of *Globigerina pachyderma* in top samples of cores. The position of the 7.2°C surface-temperature isotherm is shown.

It is evident that the method of climatic interpretation which depends upon variations in relative numbers of several different species of planktonic Foraminifera is inapplicable to the cores from the Arctic Ocean, where only a single species, *Globigerina pachyderma*, is present. However, zones defined by wide variations in the abundance of *G. pachyderma* in a unit weight of sediment occur in these cores. Climatic records inferred from variations in the abundance of *G. pachyderma* in six Arctic cores are shown in Fig. 7. The dashed lines connect points indicating a faunal change which is considered to mark the end of the last ice age. The evidence seems to indicate that cores 38 to 40 pass through layers which possibly were deposited during an interglacial age. If this is the case, the time interval represented by the stratigraphically longest section (in core 40) is, according to the chronology of Ericson *et al.* (*6*), about 140,000 years.

Since understanding of the climatic history of the Arctic Ocean is important to certain theories of causation of the Pleistocene ice ages, we have proceeded with much caution in interpreting the variations in abundance of *Globigerina pachyderma.* We have examined the possibility that the biological productivity of the species has remained fairly constant through time and that mechanical or chemical processes intermittently at work on the sea floor may have brought about the observed variations in the ratio of the number of tests to weight of sediment. However, we can find no evidence that variations in abundance from level to level are due to periodic sweeping together of the tests on the sea floor by deep currents, to dispersal of the tests by temporary increase in rate of accumulation of fine mineral particles, or to chemical solution of the tests after deposition. In the absence of such evidence and in view of the high probability that the climatic changes of the Pleistocene had some effect upon biological productivity in the Arctic Ocean, we feel that it would be gratuitous to assume some unknown mechanical or chemical process acting on the tests on the sea floor to explain the variations in abundance.

One mode of sediment emplacement may have had some influence upon the vertical distribution of *Globigerina pachyderma* in the cores—that is, ice-rafting of old tests from shallow water. That the variations in abundance are due solely to this cause is virtually disproved by two dates obtained by the radiocarbon method which show that the upper part of the upper layer in which *G. pachyderma* is abundant is less than 11,000 years old. Evidently a fairly large proportion of the tests in these samples were secreted after the postglacial moderation in climate.

In our opinion climatically controlled variation in the thickness and continuity of the ice cover in the Arctic Ocean is the only plausible explanation for fluctuations in the number of tests of *Globigerina pachyderma* in a unit weight of sediment. The drastic reduction in the ratio of tests to sediment below the uppermost zone of abundant tests records, we believe,

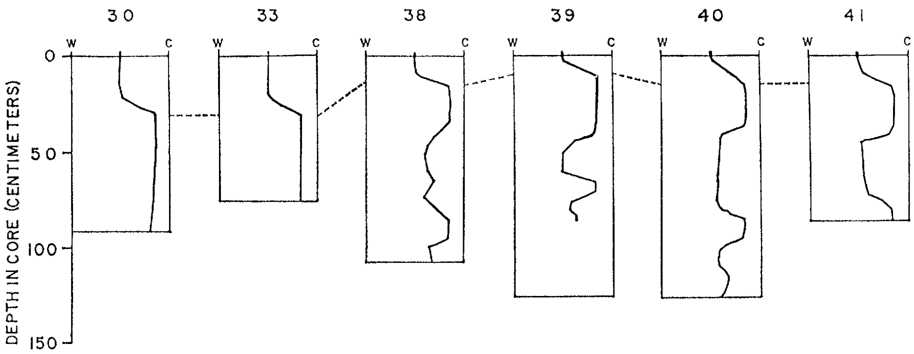

Fig. 7. Climatic curves based on variations in abundance of *Globigerina pachyderma* in six deep-sea sediment cores from the Arctic Ocean. *W*, Relatively warm climate; *C*, relatively cold climate. Present climate is plotted on the midpoint between *W* and *C*, and inferred past climate is plotted with respect to it. The dashed lines connect faunal and climatic changes believed to have occurred at the end of the last ice age.

a time when photosynthesis was reduced because the cover of sea ice became thicker and more continuous. The complete absence of *G. pachyderma* in the corresponding zone of the cores from the Bering Strait sector presumably indicates that the ice in this part of the Arctic Ocean was sufficiently thick to halt photosynthesis completely, or at least to reduce it below some minimum rate necessary for the existence of *G. pachyderma.* The absence of ice-rafted detritus in the layers containing no *G. pachyderma* in the cores from the Bering Strait sector we attribute to the rigidity of the ice cover in that particular region. The only alternative explanation for the absence of ice-rafted detritus is the supposition that this part of the Arctic Ocean was open water without drifting ice. Two facts make it highly unlikely that this second explanation is the correct one: (i) the absence of evidence of planktonic life in the zone without ice-rafted detritus, and (ii) evidence of ice-rafting throughout the cores from the Ellesmere Island sector. If drifting ice carrying terrigenous detritus was plentiful in the Ellesmere Island region during the Late Pleistocene, it is hardly conceivable that some would not have drifted into the Bering Strait sector. As we see it, only a continuous cover of rigid sea ice could have acted as an effective barrier.

Radiocarbon dating of samples from sediment cores raised in the Atlantic and Caribbean has shown that a moderation in climate, as indicated by a change in the dominant species of planktonic Foraminifera, took place about 11,000 years ago (see *6, 24*). This is considered to be the date for the end of the last ice age. Two of the three ages determined by assay of the carbonate fractions (mostly tests of *Globigerina pachyderma*) of samples from the Arctic Ocean fall within the past 11,000 years. The two ages are 4800 ± 700 years and 9300 ± 180 years. These ages, unless spuriously low, indicate that *G. pachyderma* has been living in the Arctic Ocean during postglacial time, and that at least the upper part of the upper layer of sediment, with its evidence of climatic moderation in the form of abundant tests of *G. pachyderma,* must be contemporaneous with the uppermost layer of sediment in the North Atlantic, which also gives evidence of climatic moderation.

However, an age of 25,000 ± 3000 years determined by assay of a composite sample consisting of the basal 3-centimeter sections from the layer of abundant *Globigerina pachyderma* in four cores (cores 38–41) from the Bering Strait sector indicates that climatic moderation took place some 14,000 years earlier in the Arctic Ocean than in the Atlantic.

To what extent can these radiocarbon ages be accepted? We can think of no effect which could make the ages spuriously low. On the other hand, certain conditions in the Arctic Ocean would tend to make the ages spuriously high by some unknown amount. Among these are: (i) contamination of the samples by detritus from old carbonate rocks; (ii) incorporation of old carbon during secretion of the foraminiferal tests; and (iii) redeposition of old tests of *Globigerina pachyderma* by ice-rafting. Whether any one of these influences, or all working together, can account for the seemingly anomalous relationship among the radiocarbon ages is a question which cannot be answered on the basis of our present information.

Conclusions

The cores from the Norwegian and Greenland seas demonstrate the essential similarity between depositional processes in those seas and in the Atlantic. As in the Atlantic, there is clear evidence of the importance of slumping and of turbidity currents in redistributing sediments and in modifying the depositional record during post-glacial time. In contrast, sediment believed to have been deposited during the last ice age is predominantly of glacial marine facies. Spitsbergen and the general region of the Barents Sea are the most probable sources of the ice-rafted material.

The fluctuations in numbers of tests of *Globigerina pachyderma* in cores from the Arctic Ocean indicate a climatically controlled variation in the thickness and continuity of the ice cover of the Arctic Ocean.

From our study of coiling direction in *Globigerina pachyderma* we have found that a northward shift of the 7.2°C isotherm took place at the end of the last ice age, and that the isotherm has never extended into the Norwegian Sea during the last 70,000 years.

The evidence in the cores indicates that the net movement of floating ice must have been from north to south in the eastern half of the Norwegian Sea, in contrast to the south-to-north current now flowing there. The evidence indicates that there was a confluence of ice drifting from the northeast and ice drifting from the southeast off the coast of Norway at about latitude 62° N.

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Information-Processing Models in Psychology

Though hard to present and verify, they open up basic new theoretical and methodological opportunities.

Walter R. Reitman

In 1957, Newell, Shaw, and Simon (*1*) published a description of their Logic Theorist. A program for proving theorems in elementary symbolic logic, the Logic Theorist could be used to generate behavior from a digital computer. Newell, Shaw, and Simon thus were able to demonstrate that it actually was able to solve problems only humans had been able to solve before.

It soon became apparent that information-processing programs like the Logic Theorist were of great interest to psychology. They incorporated strategies and rules of thumb similar to those used by humans, and the behaviors they generated were in some ways strikingly similar to the behaviors of humans working at the same problems. As a result, there has been a vigorous growth in psychological research utilizing information-processing methods and concepts. In addition to problem-solving programs, there now are programs that simulate learning, perception, attitudinal processes, understanding, and even neurotic personality processes, as well as a growing literature dealing with the relation of this work to other forms of psychological theory and research (*2*).

Information processing is still far from integrated into the main body of psychological thought, however, and because it is complex and new, rather than simply a new twist to widely accepted ideas and procedures, the advantages and limitations involved are only imperfectly understood. Therefore, after characterizing the approach and some of the ways it has been regarded and used, we will examine some of the major questions that must be dealt with if these techniques and concepts are to achieve in full the general psychological significance now being claimed for them.

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